Interannual variations in river water content and distribution over the Laptev Sea between 2007 and 2011: The Arctic Dipole connection

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Highlights

- Link between Arctic Dipole anomaly and river water content in the Laptev Sea
- Laptev Sea river water might be linked to the Arctic-wide freshwater content
- The Laptev Sea could contributes up to 20% of the Arctic-wide freshening

Abstract

Five years of oxygen isotope and hydrological surveys reveal interannual variations in the inventory and distribution of river water over the Laptev Sea. In 2007, 2009 and 2010 relatively low amounts of river water (≤1500 km^3) were found and were mostly located in the southeastern Laptev Sea. In 2008 and 2011, high amounts of river water (~1600 km^3 and ~2000 km^3) were found, especially in the central and northern part of the shelf, suggesting a northward export of this water. This temporal pattern is coherent with the summer Arctic Dipole index that was higher in 2008 and 2011. Our results suggest that the Arctic Dipole might influence the export of river water from the Laptev Sea. Moreover, the river water inventory in the Laptev Sea seems related to the freshwater content of the Arctic Ocean with a 2 years lag.

Keywords: Hydrology, Arctic Ocean, Laptev Sea, oxygen isotope, river water, Arctic dipole

1. Introduction

During the last decades, multiple studies highlighted decadal and annual variations in liquid freshwater storage in the Arctic Ocean [*Polyakov et al.*, 2008; *Proshutinsky et al.*, 2009; *Morison et al.*, 2012; *Krishfield et al.*, 2014; *Rabe et al.*, 2014]. Notably, it has been estimated that the liquid freshwater content in the Beaufort gyre increased by about 5000 km^3, which represents an increase of 25% compared to the level of the 1970's [*Krishfield et al.*, 2014]. Moreover, a time series of liquid freshwater content was computed for the whole Arctic basin and estimated a 30% increase in freshwater storage over the 1992-2012 period [*Rabe et al.*, 2014]. However, the exact causes for this increase are still hypothetical. One explanation relies on the strengthening of the Beaufort High, which increases the anticyclonic (clockwise) wind pattern causing a convergence of fresh surface water toward the gyre's interior [*Proshutinsky*, 2002]. However, increasing freshwater content under weakened Beaufort High suggests that other factors must be considered [*Proshutinsky et al.*, 2009]. It was also suggested that runoff from Eurasian rivers could be diverted eastward to the Canadian basin under an increasingly positive Arctic Oscillation Index (from 2005 to 2008), highlighting the importance of the pathway by which freshwater is exported from the Eurasian shelves on the global freshwater budget of the Arctic [*Morison et al.*, 2012].

The Arctic Ocean receives 11% of the global riverine freshwater discharge [*Fichot et al.*, 2013]. This freshwater contributes to the strong stratification that characterizes the upper layers of the Arctic Ocean and insulates the perennial sea-ice cover from heat contained in the warm Atlantic-derived waters [*Aagaard et al.*, 1981]. The Lena River is one of the largest Arctic rivers, delivering around one fifth of total river water to the Arctic Ocean. The river water discharging into the Laptev Sea can be exported to the Arctic Ocean interior directly at the northward shelf break or to the Canadian part of the basin after being advected eastward [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, 2008]. Thus, interannual variation in the hydrology of the Laptev Sea can significantly influence the structure of the Arctic halocline and consequently the freshwater inventory of the Arctic Ocean [*Johnson and Polyakov*, 2001; *Bauch et al.*, 2009; *Morison et al.*, 2012].

It has been suggested that the Laptev Sea summer surface hydrography is mainly controlled by the dominant winds [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, 2008]. Two different atmospheric regimes are thought to characterize the eastern Siberian shelves: 1) An anticyclonic regime caused by a strong Siberian High and a suppressed Icelandic Low and 2) a cyclonic regime driven by a weaker sea level pressure (SLP) in the western Arctic (i.e. a reduced Siberian High) and a strong Icelandic Low that extents into the Barents and Kara Seas [*Johnson and Polyakov*, 2001]. During the anticyclonic phase offshore winds shift the Lena River plume northward while during the cyclonic phase, eastward along-shore winds push the Lena river water into the East Siberian Sea [*Dmitrenko et al.*, 2005]. This pattern was observed in river water inventory along the 130°E meridian in cyclonic (1994) and anticyclonic (1999) years [*Bauch et al.*, 2009]. Moreover, it was also observed beyond the Laptev Sea shelf that years with positive SLP anomalies north of the Laptev and East Siberian Seas (1995 and 2005) were characterized by a higher northward export of river water [*Bauch et al.*, 2011].

However, the Laptev Sea hydrography might also be influenced by pan-Arctic atmospheric patterns (SI 1) as the Arctic Oscillation or the North Atlantic Oscillation [*Johnson and Polyakov*, 2001; *Peterson et al.*, 2002; *Steele*, 2004]. Moreover, recent evidence highlighted a dipole-structured anomaly in the Arctic atmosphere with its two poles distributed between the Laptev and Kara and the other one located from the Canadian Archipelagos through Greenland to the Nordic Seas [*Wu et al.*, 2006; *Wang et al.*, 2009]. This atmospheric pattern, referred as the Arctic Dipole, can influence the intensity of the Beaufort Gyre and the Transpolar Drift, the latter being a key part in the export of water and ice from the Laptev Sea [*Wu et al.*, 2006; *Wang et al.*, 2009; *Overland et al.*, 2012]. During positive Arctic Dipole summer Anomaly (AD), there is a negative pressure anomaly in the Kara Sea and a positive in the Beaufort Gyre, which creates anomalous winds that blow from the Siberian shelves toward Fram Strait, enhancing the strength of the Transpolar Drift while oppositely directed winds slowing the Transpolar Drift and restraining runoff along the Siberian coast during negative AD [*Wu et al.*, 2006; *Wang et al.*, 2009; *Overland et al.*, 2012; SI 1]. Therefore a comparison with hydrographic field data is mandatory in order to fully understand the link between the different atmospheric and hydrologic forcing and the freshwater export mechanisms over the Laptev Shelf and thus to eventually detect the long-term tendency of fresh water storage associated with climate change. Using field measurement of oxygen isotope ($\delta^{18}O$) and salinity we estimated the river water distribution and inventory over the Laptev shelf from 2007 to 2011 and compared these with atmospheric and hydrologic forcing.

2. Methods

Samples were collected during TRANSDRIFT expeditions in Arctic summer 2007 (29/08 to 17/09), 2008 (07/08 to 25/09), 2009 (09/09 to 16/09), 2010 (09/09 to 20/09) and 2011 (25/08 to 04/09) (Figure 1). Water samples were taken with a Conductivity-Temperature-Depth (CTD)-rosette. Individual temperature and conductivity measurements were obtained using Sea-Bird SBE-19+ with accuracy

±0.005 ºC and ±0.002 S/m in conductivity. In addition to CTD measurements bottle salinity was determined directly from the same water samples taken for $\delta^{18}O$ analysis using an *AutoSal 8400A salinometer* (Fa. Guildline) with a precision of ±0.003 and an accuracy of at least ±0.005. Oxygen isotopes were analyzed at the Leibniz Laboratory (Kiel, Germany) except the 2010 samples, which were analyzed at the Stable Isotope Laboratory (Oregon State University, United-States). All isotope measurements were performed using the classical CO_2-water equilibration method [*Epstein and Mayeda*, 1953]. The overall measurement precision for all $\delta^{18}O$ analysis was ± 0.04‰ or better. The ^{18}O / ^{16}O ratio is given in respect to V-SMOW in the δ-notation [*Craig*, 1961].

The river water contribution can be quantified by applying a mass-balance calculation [*Bauch et al.*, 1995, SI 2 and 3]. River water inventories were estimated by integrating the fractions of river water over the whole water column, which yields the averaged thickness of the water column containing pure river water. The inventory was calculated using the averaged thickness of river water extrapolated over the surface using the weighed-average tool in Ocean Data View. We strategically divided the Laptev Shelf into 4 parts in order to track the river water inventory distribution annually (Figure 1, SI 4). We hypothesized that during typical “offshore year” the majority of the river inventory would be located within the central, north and/or west zone while during “onshore year” the river water would be mostly constrained within the southeast zone. Our field measurement did not record any evidence of river water possibly originating from the Ob or Yenisey Rivers via the Vilkitsky Strait that could have penetrated the north or northwestern part of the Laptev Shelf and reached our sampling sites (Figure 2). However, even if the main route for the Barents and Kara Seas shelf water into the Arctic is thought to be the recently identified Arctic Shelf

Break Branch and frontal system located at the Laptev Sea slope [*Aksenov et al.*, 2011; *Bauch et al.*, 2014] we cannot completely rule out the possibility that some river water from the Kara Sea reached our sampling site. The Kara Sea river water carries an isotopic signature of about -17.5‰ while the Lena is about -20‰, so a significant input of Kara Sea river water would cause an underestimation of our river water inventory [*Bauch et al.*, 1995]. If one would considers that the totality of Ob and Yenisey discharge reaches the Laptev shelf and mix with the Lena discharge, one would estimate a river water inventory 9% higher than our. Since evidences suggest that the Kara Sea river water outflow is mostly constrained far from our sampling site [*Aksenov et al.*, 2011; *Bauch et al.*, 2014], we are confident that our river water inventory is not significantly affected by this potential influx of river water characterized by a different isotopic composition.

The fact that surface salinity pattern can be maintained from summer until the polynya events [*Dmitrenko et al.*, 2010] suggests little variability from August to April-May, thus we hypothesized that our data set is representative of the summer river water distribution, which is controlled by atmospheric forcing [*Dmitrenko et al.*, 2005]. The estimated inventory is as good as possible considering the station coverage, which is limited compared to easy-reachable oceanic areas but can be considered to be extremely high for the Arctic region. So while the inventory should be considered carefully (e.g. with partly varying station coverage between years) this collection of field data provides an unparalleled insight both in space and time on the river water distribution over the Laptev Sea.

3. Results

The hydrography on the central Laptev Sea shelf (between 74 and 77.5°N along the 126°E meridian) is influenced by the large input of freshwater from the Lena River (Figure 2). From 2007 to 2011, the surface temperature varied from 0 to 8°C over this transect. In 2007 and 2008, high temperatures (> 4°C) were measured in the southern part of the profile, while in 2009 and 2010 the whole surface layer was found to be relatively cold (< 4°C). The year 2011 was exceptionally warm, with the surface layer temperature above (< 4°C) for the whole transect, with maximum temperatures (> 6°C) located in the northernmost part of the profile, which is a unique feature in our record. In 2007, 2009 and 2010 most of the surface layer was characterized by salinities over 25, except for the very southern part. However, in 2008 and 2011 most of the surface layer was fresher than 25, with a minimum (< 10) at 75°N in 2008.

From 2007 to 2011, the fraction of river water varied from 0 to 80% along the 126°E meridian (Figure 2). The strong contribution (up to 80%) of river water in the surface layer in 2008 and 2011 results in an average thickness of pure river water of ~ 9 and 11 m, respectively (SI 5). This amount was higher than in 2007, 2009 and 2010, which were characterized by a ~ 6-7 m thick river water layer. Similar interannual variations were found when calculating inventories over the whole central Laptev Sea (74-76°N; 120-135°E), which yielded 600 - 650 km^3 of river water in 2007, 2009 and 2010, much lower than the 800 and >950 km^3 estimated for 2008 and 2011, respectively (Table 1). We also found a high amount of river water (>450 km^3) in the northern part of the Laptev Sea in 2011 (76°N – 77°N), which is contrasting all other years within our dataset, where the river water inventory was relatively constant and much lower (< 300 km^3). The same holds true for the western part of the Laptev Sea, which is characterized by a high river water inventory solely in 2011 (~150 km^3). The

Lena River directly influences the southeastern part of the Laptev Sea (Figure 1). The highest inventory in this sector was observed in 2010 (~500 km^3), while all the other years on record had similar inventory values (~400 km^3), which is not coherent with the discharge variation from the Lena River (Table 1). From our record, the central Laptev Sea contained 42 to 50% of the total Laptev shelf river water depending on the year. The total amount of river water over the Laptev Sea was highest in 2011 (+28% compared to the 2007-2011 average) and 2007 and 2009 where the lowest (-16% compared to the 2007-2011 average). Total shelf river water inventory constantly represented ~2.5 times the amount of river water released by the Lena during the preceding year even though both the discharge volume and river water inventory are characterized by relatively high interannual variations (Table 1).

4. Local Forcing

The atmospheric pressure distribution over the greater Laptev Sea region is highly variable on interannual time scales and seems to be the major factor influencing the river water distribution [*Guay et al.*, 2001; *Dmitrenko et al.*, 2005, 2008; *Bauch et al.*, 2009, 2011]. Based on a simple wind-driven surface water transport model and reanalyzed SLP data, it was suggested that the third empirical orthogonal function (EOF) was the major factor to influence the export or river water from the Laptev Sea [*Bauch et al.*, 2011]. The EOF represents the spatial pattern of variability and its variation in time and is estimated by solving the eigenvalue problem for the covariance matrix [*Preisendorfer*, 1988]. While the Arctic Oscillation index was described as the first EOF of the SLP, the second EOF was recently defined as the Arctic Dipole [*Thompson and Wallace*, 2000; *Wu et al.*, 2006]. The third EOF of the SLP over the Laptev Sea area was linked to the variation of local low pressure systems generated over the Siberian landmass during summer, which are thought to greatly influence the distribution of river water over the Laptev Sea [*Bauch et al.*, 2011].

When looking at the SLP in the Laptev Sea region over the summer months (June-July-August-September: JJAS), a spread of low-pressure system over the whole Siberian coast is observed in 2007, 2008 and 2011 (SI 6). However, in 2009 and 2010, lows were either centered over the central Kara Sea (2009) or over the Kara Sea coast (2010). On the other hand, small-scale features seems to have somehow created local SLP minimum over the Laptev Sea (or just north of it) with isobars being perpendicular to the coast from 2007 to 2010 while in 2011 the isobars are parallel to the coast. This contrast with the simple north-south SLP gradient previously highlighted for 1994 and 1999 that were respectively categorized as typical offshore and onshore years [*Bauch et al.*, 2009]. Despite observing typical offshore and onshore river water distribution and inventory between 2007 and 2011 we did not observe the atmospheric setting that was previously thought to be typical for offshore or onshore years [*Dmitrenko et al.*, 2005; *Bauch et al.*, 2009, 2011]. This suggests that different forcings might have controlled the river water distribution from 2007 to 2011 compared to the last decades. This could be linked to the recent observation that the Arctic Dipole intensity has increased over the Arctic Ocean since 2007 [*Overland et al.*, 2012]. This could also explain previous observations that highlighted a difference in the river water inventory on the continental slope north of the Laptev Sea between 1995 and 2005 despite both years being characterized as “offshore years” based on the dominant SLP distribution [*Bauch et al.*, 2011].

5. Pan-Arctic Atmospheric Forcing

The Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) are often discussed in order to explain the freshwater content of the Arctic Ocean and shelves [*Steele and Ermold*, 2004; *Steele et al.*, 2004; *Morison et al.*, 2012]. When averaging the AO index for summer months (June-Sept), 2009 was the year with the most negative AO, which is not coherent with low observed freshwater storage on the central Laptev Sea shelf and neither with high amount of freshwater found in the southeast part of the shelf. Moreover, we observed an increase of 30% in the freshwater inventory from 2007 to 2008 despite an invariable AO index, a situation similar to a 47% increase in river water between 2010 and 2011 despite a similar AO index. While there is evidence that the AO influences the Arctic-wide circulation [*Morison et al.*, 2012], our record suggests that it is not the major factor controlling the freshwater storage neither its distribution over the central Laptev Sea shelf. This is in agreement with earlier findings that the minor components of the EOF have a larger impact on the freshwater distribution north of the Laptev Sea shelf break than the 1st EOF that defines the AO [*Bauch et al.*, 2011]. Four out of our 5 years on record indicate that the river freshwater inventory follows the pattern predicted by the NAO tendency. Nevertheless, 2010 was characterized by a low NAO but the river water was diverted eastward as is typical for positive NAOs. Overall our inventories seem to generally respond to the NAO index, although some additional factors might impact the distribution of river water over the Laptev Sea shelf, such as the Arctic Dipole.

The summer (JJAS) AD index is characterized by the same trend as our freshwater distribution and inventory with the highest values in 2008 and 2011 and the lowest in 2007 (Table 1, Figure 3). Thus, our data suggest that the Arctic Dipole summarizes atmospheric conditions that dominate the distribution and fate the Laptev Sea river runoff for the 2007-2011 period, which could imply a recent increase in the importance of the 2^{nd} EOF in regard to the distribution of river water over the Laptev Sea.

6. Impact of river freshwater export from the Laptev Sea on the Arctic

When comparing the interannual variation of river water inventory over the Laptev Sea we found no relationship (and neither a 1-year lagged) with the Arctic-wide freshening estimated by Rabe and colleagues [2014]. This is not surprising since the total Laptev shelf inventory represents about ~2.5 times the amount of river water released by the Lena during one year, and thus it seems unlikely that this water significantly impacts the arctic-wide budget within only a year. The best fit was found when comparing the Laptev Sea river water inventory with the Arctic-wide liquid freshwater inventory with a two-years lag (Figure 3), which also holds true when comparing with the liquid freshwater inventory of the Beaufort Gyre [*Krishfield et al.*, 2014]. The fit with a 2-year lag is even better when only considering the inventory of the central Laptev Sea, which would suggest a transport time of about 2 years for the river water that is advected northward to reach the Arctic Basin and/or the Beaufort Gyre. If we consider a two-year lag, the 200 km^3 increase in river water on the central Laptev Sea shelf between 2007 and 2008 would account for 50% of the increase in liquid freshwater in the Beaufort Gyre from 2009 to 2010 [*Krishfield et al.*, 2014] and ~20% of the Arctic-wide freshening for the same period [*Rabe et al.*, 2014]. Thus, our data suggest that the Arctic Dipole might play a significant role for the Siberian Shelves river water inventory and consequently on the Arctic Ocean freshwater budget.

7. Concluding Remarks

This five-year isotopic survey of the Laptev Sea highlights the strong link between atmospheric patterns and the Laptev Sea hydrography and suggests that, for the 2007-2011 period, the Arctic Dipole has exerted a strong influence on the distribution and export of river water from on the Laptev Sea shelf. This is different than the previous decades, when the local SLP pattern (3rd EOF) was the main driver of the river water distribution and export.

An analysis of recent Arctic atmospheric patterns suggested a persistent change in early summer (June) SLP for 2007-2012 that was recognized as the Arctic Dipole [*Overland et al.*, 2012]. This feature might be linked to an earlier snow or ice cover loss over high latitudes, notably over the Hudson Bay since it would allows an earlier warming of those waters and a subsequent increase in SLP [*Joly et al.*, 2010; *Overland et al.*, 2012]. Potential impacts of this newly persistent pattern are increased Arctic sea ice loss in summer, long-lived positive temperature anomalies and ice sheet loss in west Greenland, and increase in Arctic-subarctic weather linkages through higher-amplitude upper-level flow [*Overland et al.*, 2012]. Our results suggest that it also plays an important role on the freshwater budget of the Arctic Ocean via its influence on the freshwater export from the Siberian Seas, notably the Laptev Sea. Thus it highlights the need of research focused on atmosphere-ocean interaction in order to understand potential impact of high-latitude warming on the global Arctic Ocean freshwater budget as well as increasing effort to understand the role of Siberian shelves on the Arctic Ocean freshening.

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Figure captions

Figure 1. Map of the Laptev Sea with sampling stations along with the salinity versus $\delta^{18}O$ plot for year 2007 (Black), 2008 (Blue), 2009 (Green), 2010 (Orange) and 2011 (Red). Rectangles on the map represent the interpolation zones used to calculate the river water inventory. The black line in the plot represents the mixing line between the river and seawater end-members.

Figure 2. The temperature (CTD measurement), salinity (from sampled bottle) and river water (from sampled bottle) fraction profile against depth (m) in the central Laptev Sea (74-77°N along the 126°E meridian) for 2007 to 2011. Dots represent each sample taken (exact dates of sampling are listed in the online data).

Figure 3. Plot of the Arctic Dipole (AD), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) against the central Laptev Sea river water inventory (upper panel) and of the liquid freshwater inventory (in 10 000 km^3) against the 2-yrs lagged central Laptev Sea river water inventory (bottom panel).

Table captions

Table 1. River Water Inventory

River water inventory estimate for the different sectors of the Laptev Sea. Stars indicate data estimated from the average of similar years in term of inventory distribution (SI 4). River water discharge from [a]*Fedorova et al.*, 2013, [b]*Bauch et al.*, 2013. From 2007-2010, the Lena freshwater discharge was relatively constant, except for 2011 where the discharge was estimated to be higher (+ 25%). The river water inventory was compared to atmospheric indexes: Arctic Oscillation Index (AO; June-July-August-September-averaged (JJAS), [c]NOAA Climate Prediction Center [2014]), North Atlantic Oscillation Index (NAO; JJAS averaged, [c]NOAA Climate Prediction Center [2014]) and the Arctic Dipole Index (AD; JJAS averaged, [d]*Overland et al.* [2012]) for 2007-2011 are listed.

Tables

Table 1. River Water Inventory

	River water inventory (km^3)					Lena river	AO[c]	NAO[c]	AD[d]
Years	Central	Southeast	North	West	Total	Discharge volume (km^3)			
2007	608	368	261	89*	1375	578[a]	-0.2	-0.3	-1.4
2008	810	416	298	89*	1613	585[b]	-0.2	-0.7	-0.5
2009	652	396*	252	91	1395	637[b]	-0.5	-0.5	-1.0
2010	653	503	262	87	1505	525[a]	-0.1	-0.8	-1.0
2011	961	405	491	154	2012	707[a]	-0.4	-0.9	-0.4

River water inventory estimate for the different sectors of the Laptev Sea. Stars indicate data estimated from the average of similar years in term of inventory distribution (SI 4). River water discharge from [a]*Fedorova et al.*, 2013, [b]*Bauch et al.*, 2013. From 2007-2010, the Lena freshwater discharge was relatively constant, except for 2011 where the discharge was estimated to be higher (+ 25%). The river water inventory was compared to atmospheric indexes: Arctic Oscillation Index (AO; June-July-August-September-averaged (JJAS), [c]NOAA Climate Prediction Center [2014]), North Atlantic Oscillation Index (NAO; JJAS averaged, [c]NOAA Climate Prediction Center [2014]) and the Arctic Dipole Index (AD; JJAS averaged, [d]*Overland et al.* [2012]) for 2007-2011 are listed.

Figures

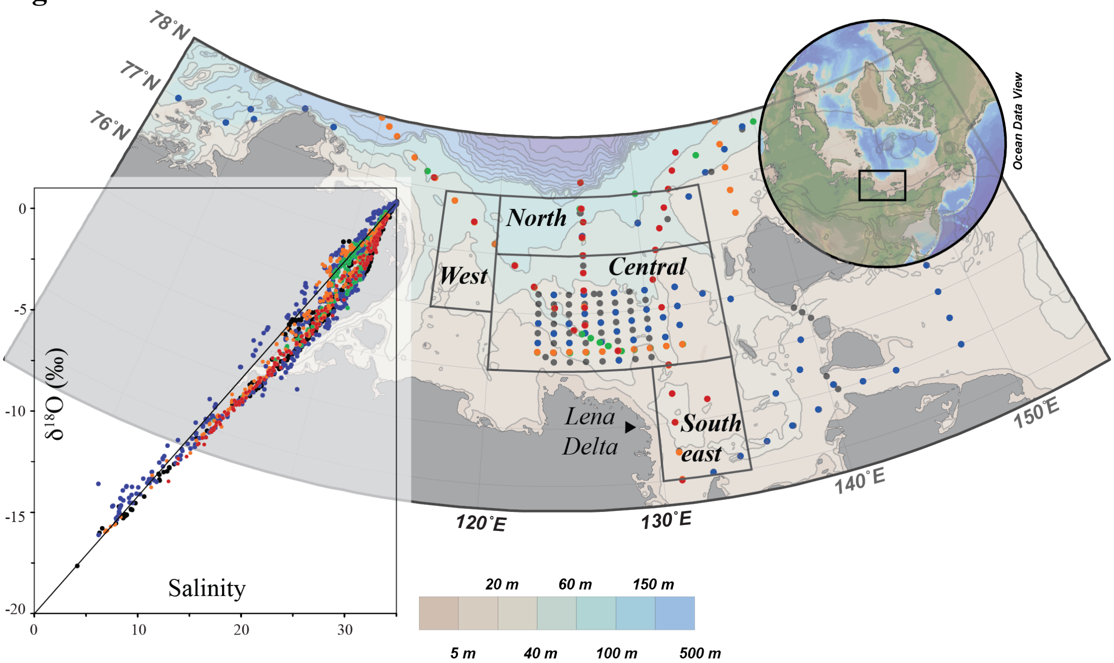

Figure 1. Map of the Laptev Sea with sampling stations along with the salinity versus δ^{18}O plot for year 2007 (Black), 2008 (Blue), 2009 (Green), 2010 (Orange) and 2011 (Red). Rectangles on the map represent the interpolation zones used to calculate the river water inventory. The black line in the plot represents the mixing line between the river and seawater end-members.

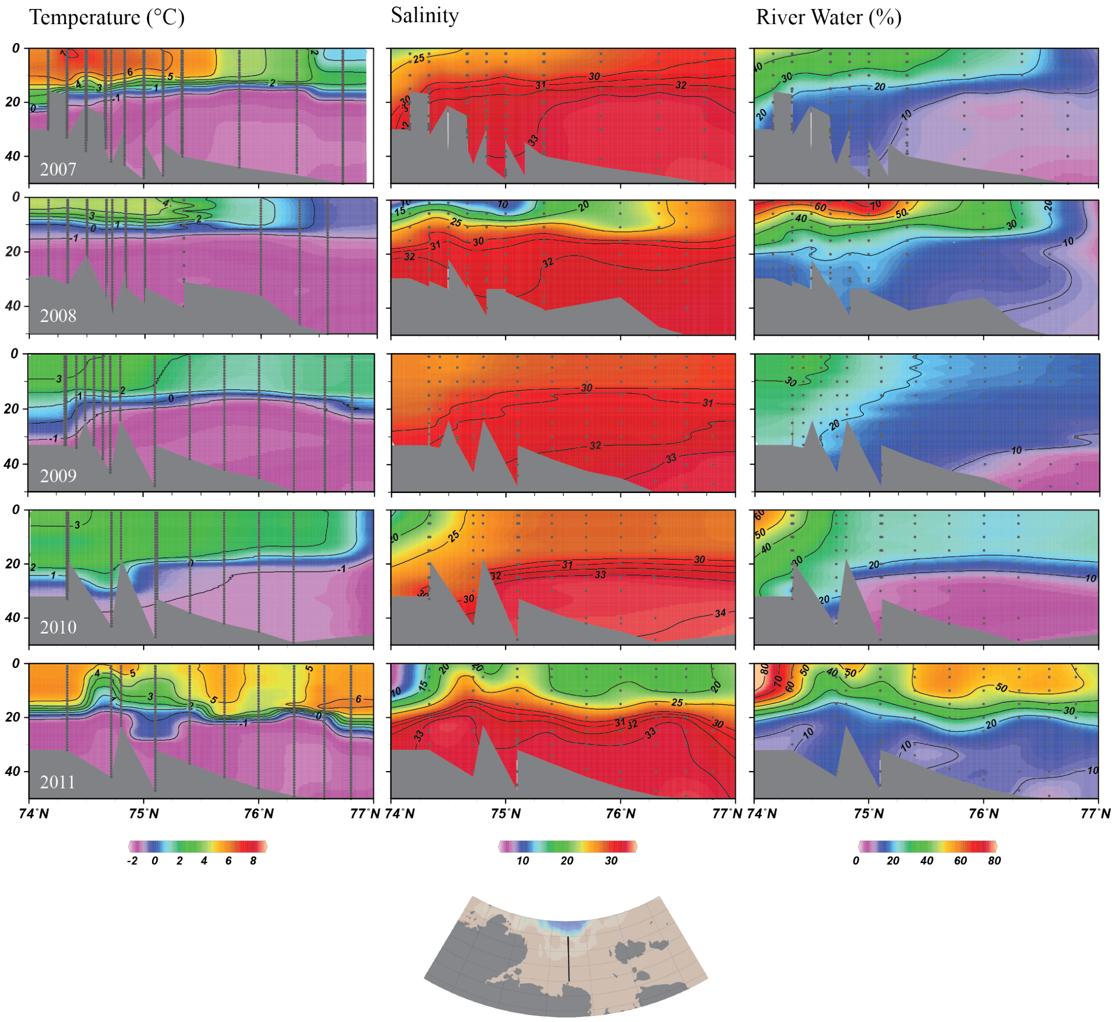

Fig. 2. The temperature (from CTD measurement), salinity (from sampled bottle) and river water (from sampled bottle) fraction profile against depth (m) in the central Laptev Sea (74-77°N along the 126°E meridian, represented by the black line on the map) for 2007 to 2011. Dots represent each sample taken (exact dates of sampling are listed in the online data).

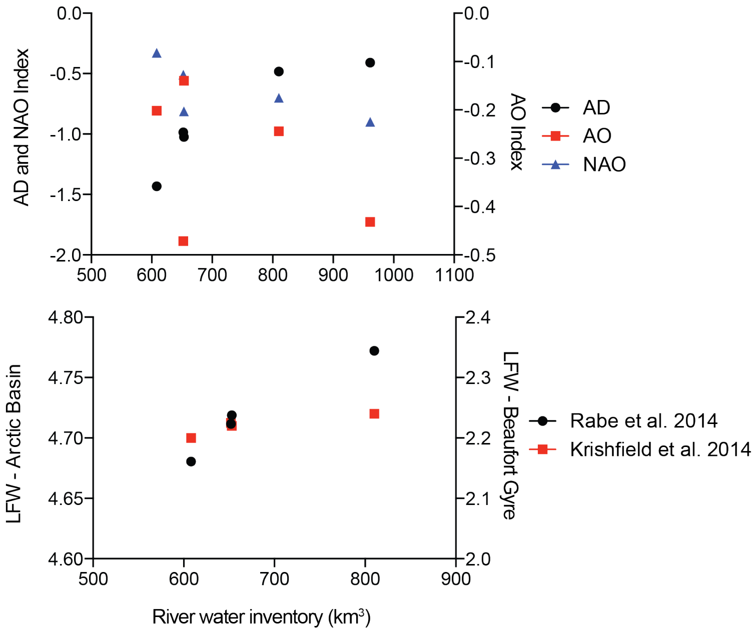

Figure 3. Plot of the Arctic Dipole (AD), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) against the central Laptev Sea river water inventory (upper panel) and of the liquid freshwater inventory (in 10 000 km^3) against the 2-yrs lagged central Laptev Sea river water inventory (bottom panel).